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High resolution wind turbine wake measurements with a scanning lidar

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Abstract. High-resolution lidar wake measurements are part of an ongoing field campaign being conducted at the Scaled Wind Farm Technology facility by Sandia National Laboratories and the National Renewable Energy Laboratory using a customized scanning lidar from the Technical University of Denmark. One of the primary objectives is to collect experimental data to improve the predictive capability of wind plant computational models to represent the response of the turbine wake to varying inflow conditions and turbine operating states. The present work summarizes the experimental setup and illustrates several wake measurement example cases. The cases focus on demonstrating the impact of the atmospheric conditions on the wake shape and position, and exhibit a sample of the data that has been made public through the Department of Energy Atmosphere to Electrons Data Archive and Portal.

1. Introduction

Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) are conducting an experiment at the SNL Scaled Wind Farm Technology (SWiFT) facility located in Lubbock, Texas [1, 2] to investigate the use of wind turbine yaw control to direct wakes for increased wind plant performance [3-5]. One of the primary objectives of the experiment is to collect experimental data to improve the predictive capability of wind plant computational models to represent the response of the turbine wake to varying inflow conditions and turbine operating states. The baseline SWiFT facility has well-instrumented meteorological towers and research turbines, but in order to adequately measure the turbine wakes, the team partnered with the Technical University of Denmark (DTU) Wind Energy Department to leverage their wake measurement expertise and their custom-built SpinnerLidar instrument, which is uniquely capable of measuring wakes at the temporal and spatial resolution required for the experiment [6-8].

Data collected as part of the multi-month field campaign will be used to improve both high-fidelity wind plant models as well as demonstrate control concepts to facilitate future wind industry technology development for reducing wake losses. To confirm model predictions, long-term continuous measurements of the wake velocity profile downwind of the turbine are needed to obtain a statistical representation. The methodology for this effort is based on a formal Verification and Validation (V&V) framework developed for the U.S. Department of Energy (DOE) Atmosphere to Electrons (A2e) initiative. This V&V framework is being used for the development and execution of a coordinated simulation and experimental program to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes [9].

The present work summarizes the experimental setup and illustrates several wake measurement example cases from the current SWiFT facility measurement campaign. The focus of this paper is to provide a few sample cases that demonstrate the impact of the atmospheric conditions on the wake shape and position, and exhibit some of the data that is available through the DOE Atmosphere to electron (A2e) Data Archive and Portal (DAP) as part of the current experimental campaign [10].



2. Experimental Setup

The primary quantities of interest for the experiment include the trajectory of the wake center, the wake deficit strength, the wake shape, and the wind turbine rotor loads and power for a range of fixed yaw offsets subjected to a range of atmospheric inflow conditions [3, 5, 11]. To meet this objective, a variety of synchronized instrumentation were integrated at the SWiFT test site, including an upstream meteorological tower, turbine structural and performance sensors and the DTU SpinnerLidar to characterize the wake center location and deficit magnitude [8, 12]. The following sections describe the experimental setup in detail.

2.1. SWiFT Site Configuration

Sandia National Laboratories operates the Scaled Wind Farm Technology (SWiFT) facility located in Lubbock, Texas. The baseline site instrumentation includes three research wind turbines (WTG) and two meteorological towers (MET) as shown in figure 1 with the relative as-built survey locations listed in table 1.

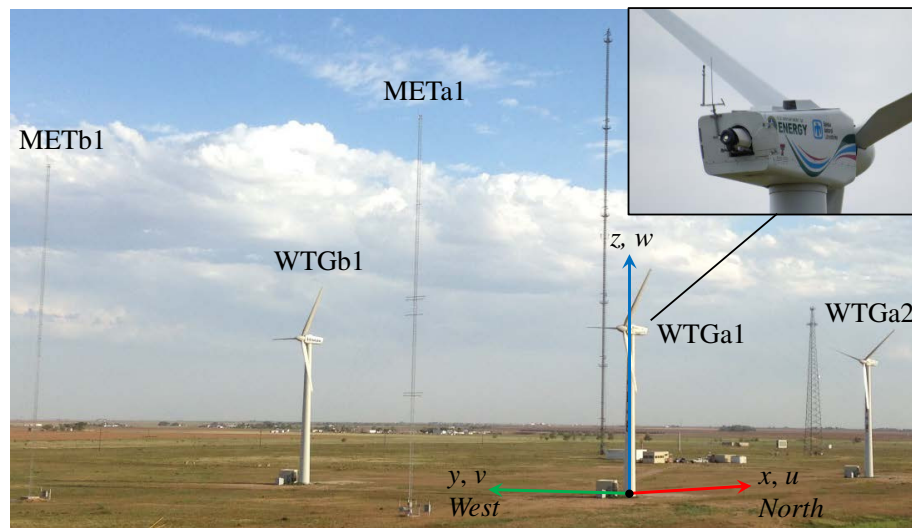


Figure 1. SWiFT site layout and coordinate system with the DTU SpinnerLidar installed in WTGa1 [1].

Table 1. As-built survey locations of the baseline SWiFT site instruments

Instrument	x (m), North	y (m), West	z (m), Base Height
WTGa1	0.00	0.00	0.00
WTGa2	134.97	0.17	0.09
WTGb1	-5.41	80.95	-0.02
METa1	-69.50	-3.29	0.22
METb1	-74.95	77.53	0.20

The layout of the SWiFT facility is seen from an overhead view in figure 2 along with the wind rose at a height of 75 m (north is 0 degrees). The met tower and the two turbines used in this campaign (METa1, WTGa1, and WTGa2) are all aligned with the predominant wind direction at the site. This configuration allows measurement of the atmospheric inflow with the met tower and measurement of the wake of the WTGa1 turbine using the nacelle-mounted DTU SpinnerLidar.

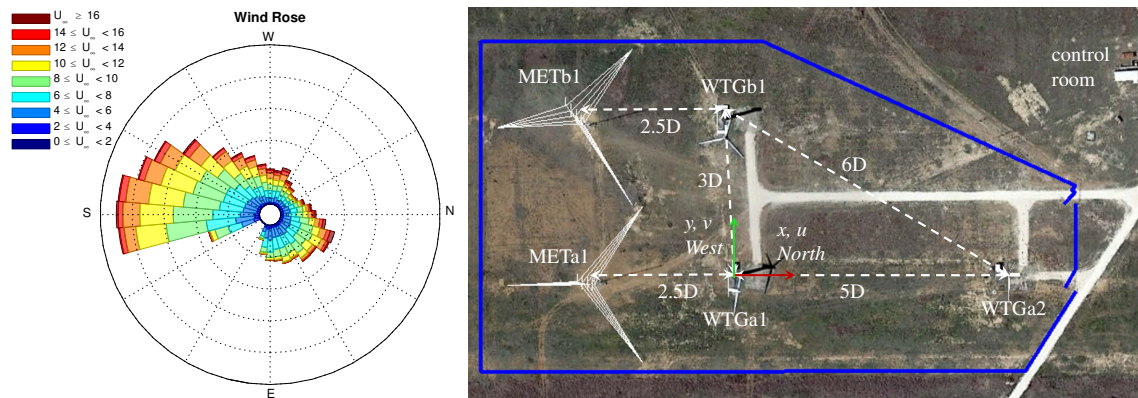


Figure 2. Top view of the SWiFT facility layout and wind rose at 75 m height ($D = 27\text{m}$) [2].

The SWiFT turbines are highly-modified Vestas V27 machines with a hub height of 32.1 meters, a rotor diameter of 27 meters, and a power rating of 192 kW. The meteorological towers are 60 m tall with a suite of atmospheric sensors located at heights as indicated in figure 3. The entire site is on a fiber optic network facilitating the logging of over 400 data channels at a frequency between 20 to 100 Hz, synched to a GPS time-signal and stored centrally in the control building shown in the upper right corner of figure 2.

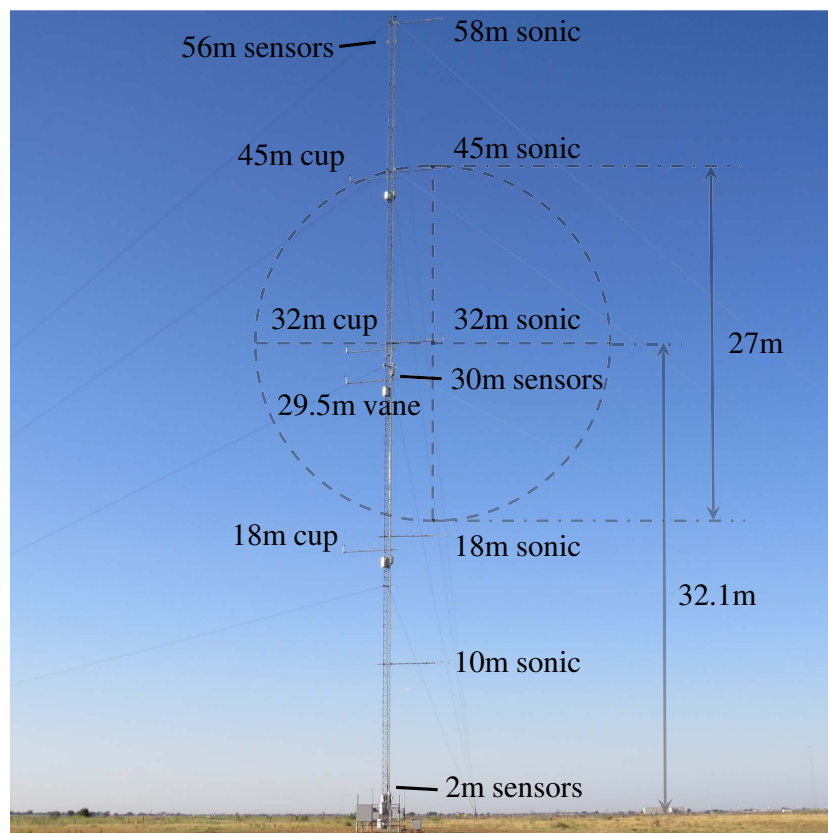


Figure 3. Photo of the METa1 with locations of the cups, vanes, sonic anemometers and atmospheric sensors (temperature, relative humidity, barometric pressure). The image was acquired looking in the Southerly direction and includes an approximate projection of the WTGa1 rotor diameter on the met tower.

2.2. SpinnerLidar Configuration

The DTU SpinnerLidar (figure 4a) is uniquely capable of measuring the wind turbine wake at the temporal and spatial resolution required for the experimental campaign. DTU developed the SpinnerLidar to be a turbine mounted lidar for rapid scanning of the wind field in a two-dimensional plane. For this experiment, the SpinnerLidar was mounted as shown in figure 1 to point out of the rear of the upwind SWiFT turbine nacelle (WTGa1), optimally positioned to capture the full wind turbine wake up to five rotor diameters downstream ($D = 27$ m). The SpinnerLidar has a scan head consisting of two co-rotating $\sim 15^\circ$ wedge-shaped prisms integrated on a ZephIR 300 continuous-wave coherent Doppler lidar. The lidar produces laser light at a wavelength of 1565 nm and was configured to stream averaged Doppler spectra at a rate of about 492 measurements per second. The prisms have a fixed gear ratio with adjustable motor settings to change the duration and number of measurements per scan (motor speed fixed for each scan) [8, 13]. The resulting rosette scan pattern is displayed in figure 4b. At each focus distance, the SpinnerLidar scans the two-dimensional surface of a sphere with an approximately 30° half angle. The lidar also has the ability to cycle through focus distances with a change in focus distance occurring in the same amount of time as a full scan (figure 4b). The position of the measurement relative to the symmetry axis is calculated from the instantaneous position of the two wedge-shaped prisms. Changes in the orientation of the rotation axis are accounted for using an integrated three-axis accelerometer.

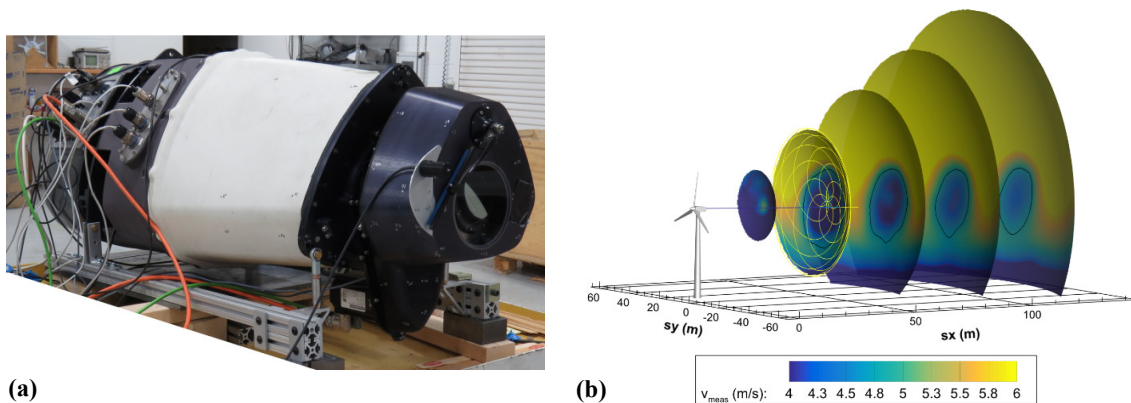


Figure 4. (a) A photograph of the DTU SpinnerLidar in the lab, and (b) the SpinnerLidar scanning pattern at the SWiFT site, overlaid on line-of-sight (LOS) speed profiles extracted from virtual lidar simulations [4, 14].

Figure 4b shows one of the scanning configurations that has been used during the wake steering experiment with rosette scans at each of 5 rotor diameter distances downstream. Each rosette pattern of approximately 984 data points takes 2 seconds to complete and another 2 seconds to refocus to each sequential measurement plane downstream. In this configuration, the lidar captures five slices of the wake about every 18 seconds. So far the lidar has captured this wake data as the turbine operated under a variety of intentional yaw offsets, or misalignments, between $\pm 10^\circ$ with respect to the predominant inflow direction and under various atmospheric conditions characterized by wind speed, temperature profile, turbulence intensity, veer, and shear. Future yaw offsets will include a range from -18° to $+25^\circ$. The lidar is mounted to a manually adjustable platform that has fine resolution ($\sim 1^\circ$) yaw shift increments to ensure the lidar field of view captures the wake at these larger yaw offsets.

2.3. Data Collection and Processing

The SpinnerLidar calculates the line-of-sight velocity from the returned Doppler spectra by calculating the median of frequencies observed within the probe volume above a noise threshold. The quality assurance and quality control (QA/QC) method removes data points that have a low level of laser signal return relative to the noise threshold as well as points contaminated with laser signal returns from stationary objects due to the introduction of slight object movement from the motion of the laser scan

pattern. The removal of points with laser returns from stationary objects primarily addresses points contaminated with ground returns and boresight returns. The boresight returns are due to laser reflections from the outer window and appear at the center of the scan pattern. Sometimes this removal includes points due to returns from the met towers, neighboring SWiFT wind turbines and other objects.

The lidar measurement location is aligned and calibrated using the method provided in Ref. [12]. The measurements are transformed into the coordinate system in figure 5 (referred to as the lidar coordinate system), where the sx direction is aligned with the centerline of the nacelle axial direction, sz is vertical, and sy is oriented to create a right-handed coordinate system. Figure 5 also shows the relationship between the overall SWiFT site coordinate system and the lidar coordinate system. The location of the measurements in the lidar coordinate system are scaled from an initial normalized frame (figure 6a, which was calibrated in Ref. [12]) using the average focus distance over the scan. The actual focus distance at each measurement point can fluctuate as high as ± 2 m. This fluctuation is relatively small when compared to the probe volume length of the lidar as shown in figure 6b, resulting in a minimal change in the corresponding velocity measurement [15, 16]. The orientation and position of the lidar relative to the ground and nacelle was determined using total station theodolite (TST) measurements [12]. The lidar roll and pitch angles are measured by a calibrated 3-axis accelerometer [12], and applied to the data to create the lidar coordinate system (sx , sy , sz).

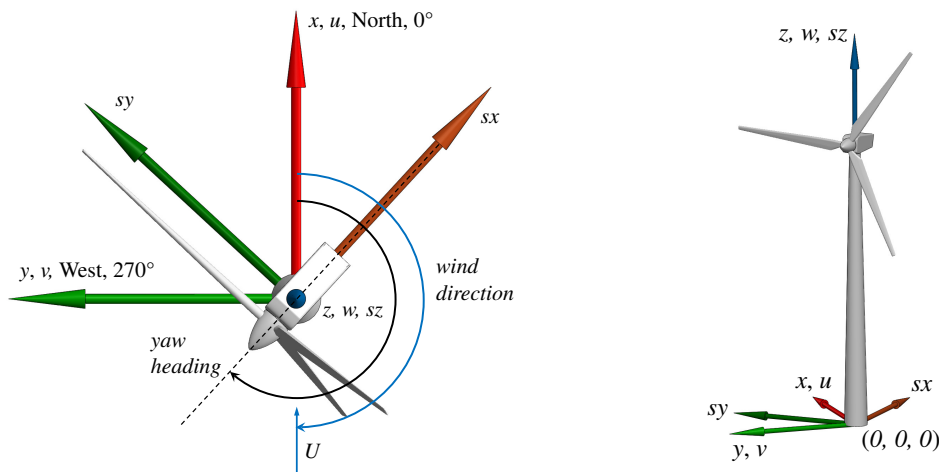


Figure 5. Schematic of the SWiFT site coordinate system relative to the lidar coordinate system (sx , sy , sz).

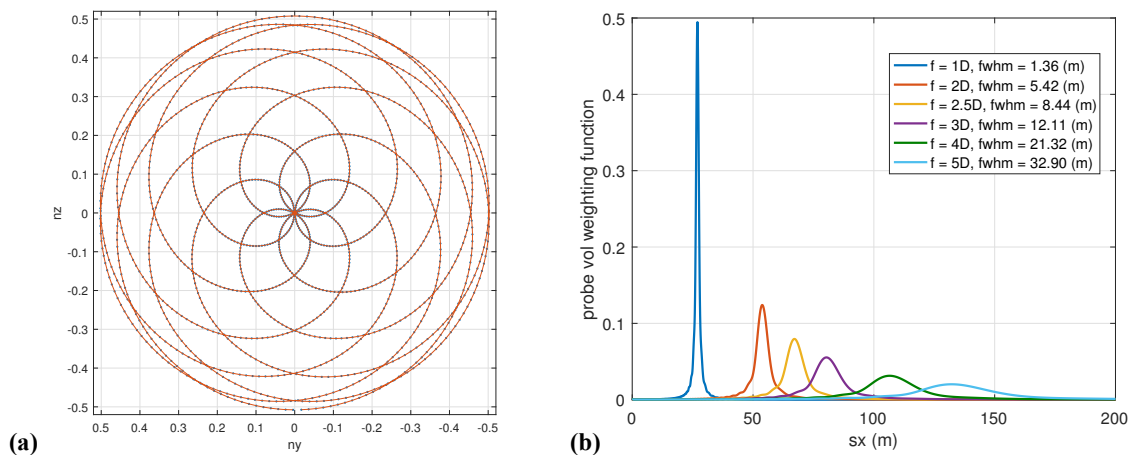


Figure 6. (a) Calibrated DTU SpinnerLidar scan points in normalized lidar coordinates and (b) lidar probe volume weighting function versus measurement distance.

The origin of the coordinate system is centered along the nacelle yaw rotation axis and located at the base of the turbine foundation. The vertical coordinate in the lidar coordinate frame matches the vertical coordinate of the SWiFT site coordinate frame, and the SWiFT site x - y plane matches the lidar sx - sy plane. Thus, the only difference between the lidar coordinate system and cardinal direction coordinate systems is due to the yaw heading of the turbine. The lidar coordinate system can be transformed into the SWiFT site coordinate system or wind direction coordinate system by applying a rotation around the sz axis with a magnitude corresponding to the yaw heading or yaw offset, respectively.

3. Results

Several wake measurement datasets are presented here, all of which strongly indicate the effect of atmospheric conditions on the wake shape and position. Figures 7 – 12 display sample contour surfaces from the measured lidar data between 1 – 5 D ($D = 27$ m) downstream of the turbine as the line-of-sight speed (v_{LOS}). The irregular scan pattern was interpolated to a regular grid using a smoothing surface fit, while the wake position was calculated using an image processing object detection method of the wake velocity deficit. The calculated wake boundary and center are displayed as a white line and black dot, respectively. The wake location in time and space is the primary quantity of interest to assess and improve the wake steering control model throughout the current experimental campaign [3, 5]. The atmospheric conditions have been calculated as defined in Ref. [2]. Specifically, the atmospheric boundary layer power-law velocity profile exponent, α , is defined in equation (1), where α was approximated using a least-squares fit of the wind speed measured by the met tower sonic anemometers at a height of 10 m, 18 m, 32 m, 45 m, and 58 m (figure 3). The power-law exponent approximation has an average uncertainty of ± 0.01 in the presented cases using 10 min. bins of sonic anemometer data.

$$\frac{U(z)}{U_{\infty, 32m \text{ Sonic}}} = \left(\frac{z}{z_{32m \text{ sonic}}} \right)^\alpha \quad (1)$$

Positive veer of the atmospheric inflow is expressed in equation (2) as a clockwise rotation of the wind direction (from an overhead view, as in figure 5) with increasing height measured across the height of the rotor. The SWiFT site atmospheric characterization reveals a stable atmospheric boundary layer is frequently required for high veer and shear profiles, positive veer is more common than negative veer, and turbulence reduces the presence of veer [2]. Only stable atmospheric cases with veer are presented because unstable and neutral cases with large amounts of veer are rare. Observation of the impact of veer on the wind turbine wake is also more difficult under neutral and unstable atmospheric inflows due to increased levels of atmospheric turbulence as compared to the stable atmosphere condition.

$$veer = \theta_{45m \text{ sonic}} - \theta_{18m \text{ sonic}} \quad (2)$$

Although the presented cases are at a range of wind speeds, the rotor is operating in region 2 or 2.5 for all cases [17]. The yaw offset of the wind turbine is described as the wind direction of the met tower hub-height sonic anemometer minus the wind turbine yaw heading (equation (3)). The wind turbine coordinate system in figure 5 defines both the wind direction and the yaw heading relative to north. Figure 5 illustrates a wind direction and wind turbine yaw heading that corresponds to a negative yaw offset.

$$\gamma_{\text{yaw offset}} = \theta_{\infty, 32m \text{ sonic}} - \psi_{\text{turbine yaw heading}} \quad (3)$$

3.1. Neutral Atmospheric Boundary Layer Case

The first case (figure 7) displays lidar data acquired during a neutrally stable atmospheric inflow as defined by the normalized Obukhov length, z/L . The turbine was operating in region 2.5, with moderate turbulence and shear in addition to low veer. The measurements in figure 7 were acquired over a duration

of 22 s with a 2 s scan rate at each focus distance (1, 2, 2.5, 3, 4, and 5 D). The wake position and shape appears to fluctuate between measurement surfaces, relative to the inflow direction.

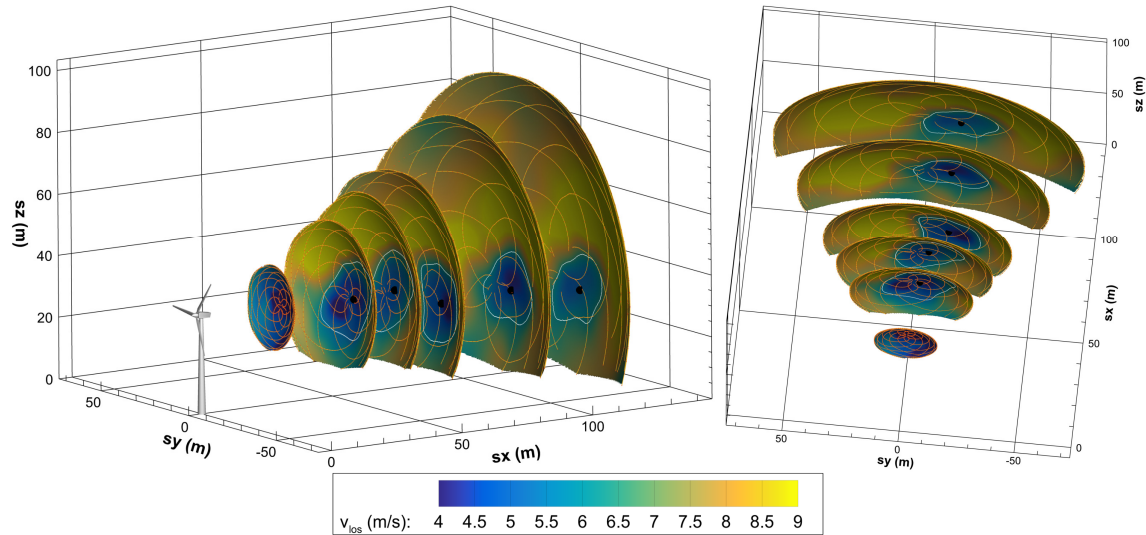


Figure 7. Example lidar measurements from 1 – 5 D over 22 s with a neutrally stable inflow: normalized Obukhov length $z/L = 0.0$, $\alpha = 0.12$, wind speed = 8.2 m/s, TI = 0.11, veer = 1.3° , yaw offset = 5.9° , and yaw heading = 243.8° degN.

3.2. Stable Atmospheric Boundary Layer with No Veer Case

The next case displays the wake under stable atmospheric conditions with low veer, shown in figure 8. The rotor is operating in region 2 with minimal yaw offset. The turbulence was very low and the shear was stronger than in the neutral case. The measurements in figure 8 were acquired over a duration of 22 s with a 2 s scan rate at each focus distance (1, 2, 2.5, 3, 4, and 5 D). Notice that the shape of the wake deficit appears round and follows the wind direction, with little fluctuation in position or shape between measurement surfaces.

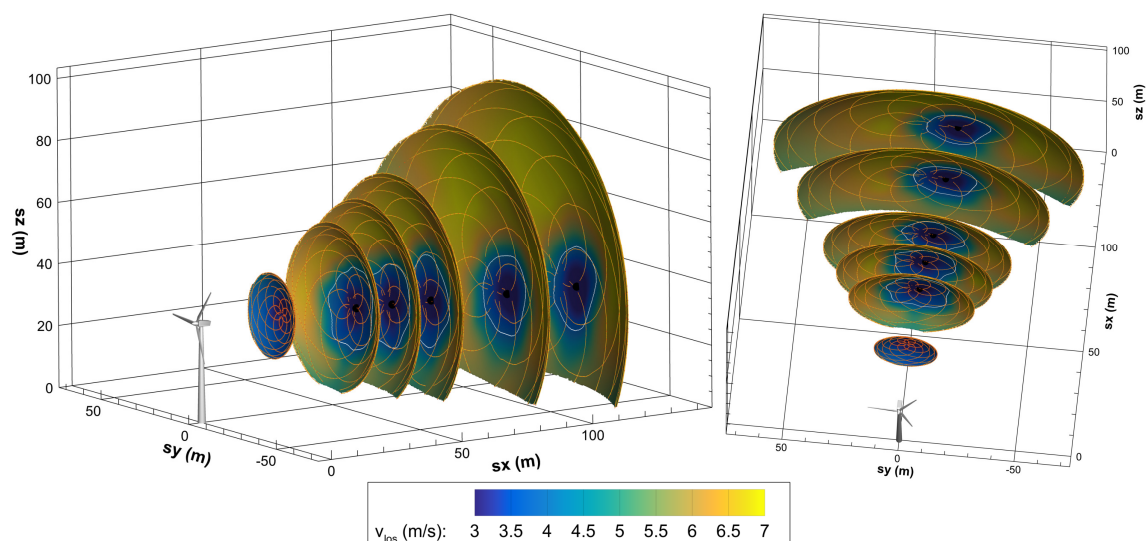


Figure 8. Example lidar measurements from 1 – 5 D over 22 s with a stable inflow and low veer: normalized Obukhov length $z/L = 3.4$, $\alpha = 0.19$, wind speed = 6.8 m/s, TI = 0.05, veer = 0.1° , yaw offset = 4.0° , and yaw heading = 236.7° degN.

3.3. Stable Atmospheric Boundary Layer with Positive Veer Case

The case shown in figure 9 is also stable, but has stronger shear and substantial positive veer. The rotor was also operating in region 2, with similar wind speed, turbulence intensity, and yaw offset as the previous stable case with minimal veer (figure 8).

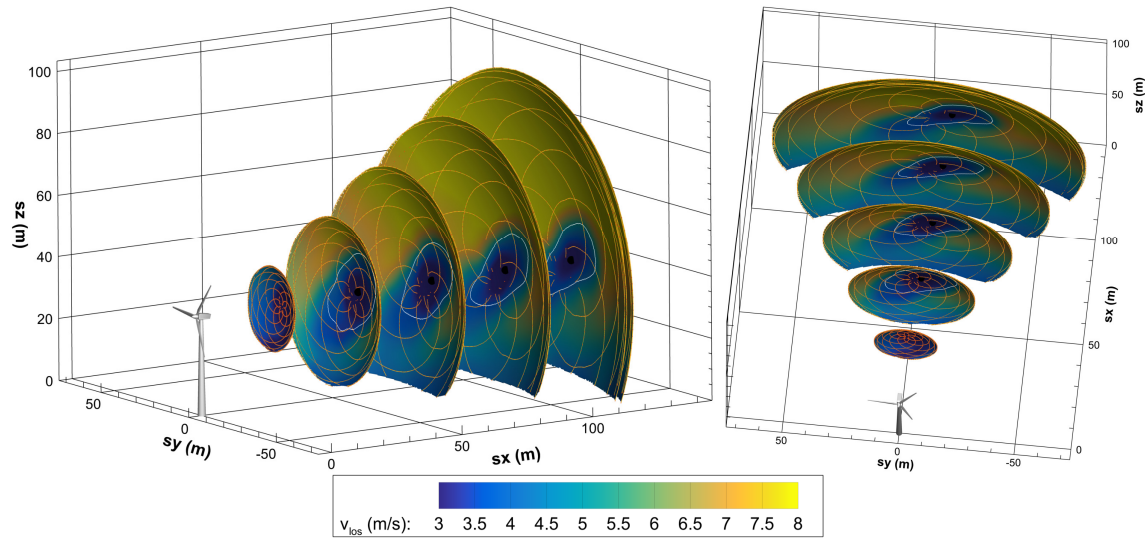


Figure 9. Example lidar measurements from 1 – 5 D over 18 s with a stable inflow and positive veer: normalized Obukhov length $z/L = 2.3$, $\alpha = 0.37$, wind speed = 6.9 m/s, TI = 0.04, veer = 14.6°, yaw offset = -0.12°, and yaw heading = 195.3 degN.

As expected, the strong positive veer causes the wake velocity deficit shape (wake shape) to skew in the direction of the changing wind direction as a function of height. The skew in the wake shape is displayed more distinctly in the flattened wake cross sections shown in figure 10 at 2 and 5 rotor diameters downstream of the rotor. The measurements in figure 9 were acquired over a duration of 18 s with a 2 s scan rate at each focus distance (1, 2, 3, 4, and 5 D). Observe that the inflow is highly stable and that even though the wake shape changes dramatically as it moves downstream, the overall wake position aligns with the flow direction, without fluctuations.

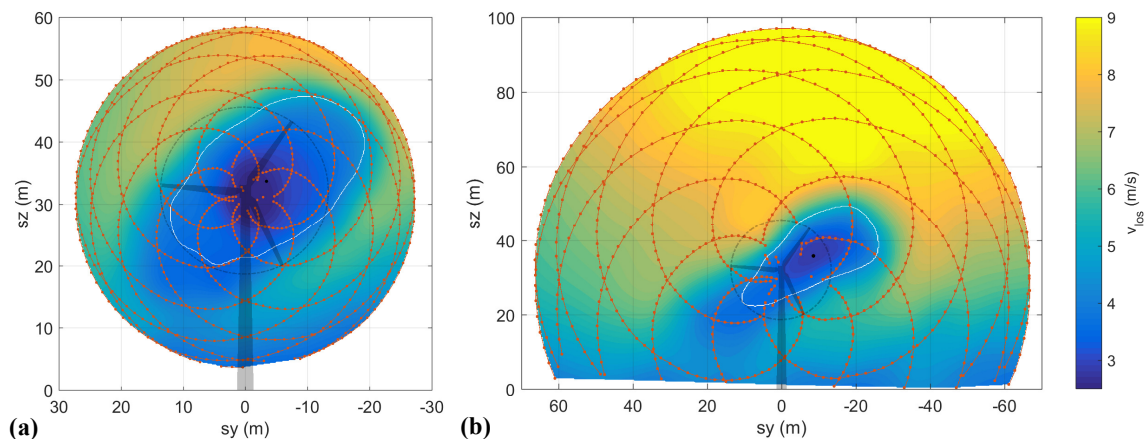


Figure 10. SpinnerLidar measurements viewed in the sy - sz plane to help visualize the impact of a highly stable, large positive veer inflow on wake shape at (a) 2 D and (b) 5 D downstream, silhouette of WTGal included for reference and scale.

3.4. Stable Atmospheric Boundary Layer with Negative Veer Case

The effect of negative veer is illustrated in figure 11, which includes the combined influence of moderate negative veer and moderate positive yaw offset on the wake shape and position. The measurements in figures 11 were acquired over a duration of 18 s with a 2 s scan rate at each focus distance (1, 2, 3, 4, and 5 D) with the turbine operating in region 2. As with the previous case, the stable atmosphere results in a wake trajectory with few fluctuations.

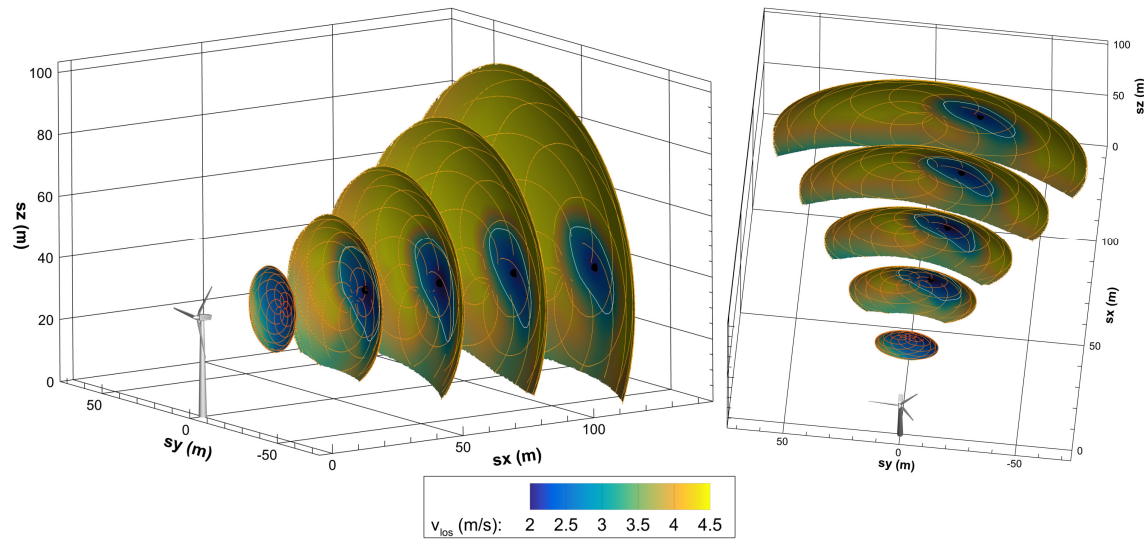


Figure 11. Example lidar measurements from 1 – 5 D over 18 s with a stable inflow and negative veer: normalized Obukhov length $z/L = 0.9$, $\alpha = 0.15$, wind speed = 4.8 m/s, TI = 0.08, veer = -5.0° , yaw offset = 10.9° , and yaw heading = 29.5° degN.

3.5. Unstable Atmospheric Boundary Layer Case

The final case (figure 12) displays the wake velocity deficit under unstable inflow conditions, commonly found during daytime (acquired at 11:51 AM CST). The wind speed places the rotor near the beginning

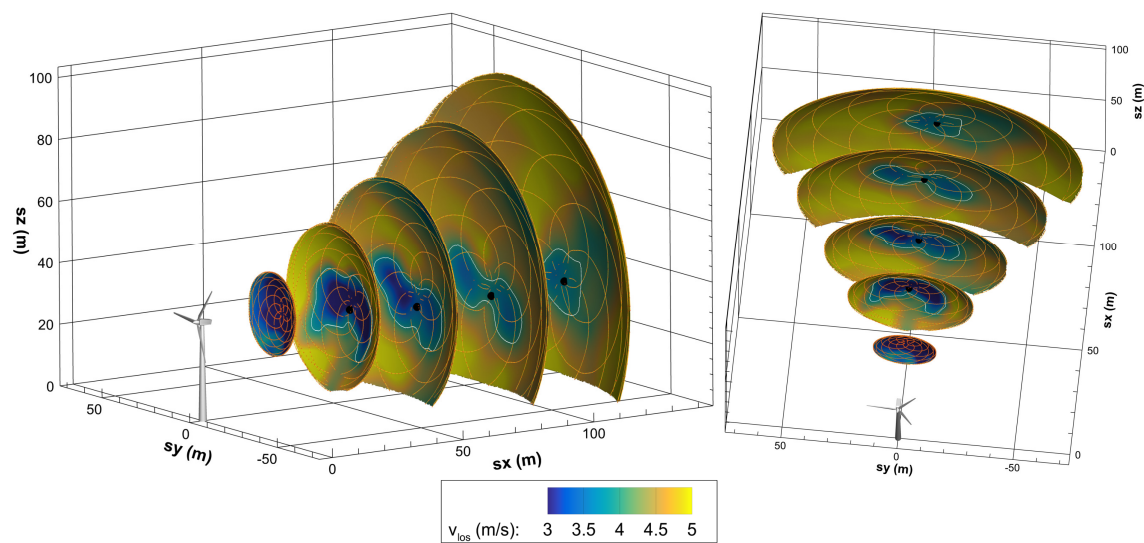


Figure 12. Example lidar measurements from 1 – 5 D over 18 s with an unstable inflow: normalized Obukhov length $z/L = -0.8$, $\alpha = 0.05$, wind speed = 5.8 m/s, TI = 0.25, veer = -2.0° , yaw offset = 5.7° , and yaw heading = 47.4° degN.

of region 2 turbine operation. Shear and veer were relatively low and turbulence relatively high, as expected during the increased mixing in an unstable atmospheric boundary layer. The wake shape is irregular since it is heavily influenced by the turbulent structures in the atmospheric boundary layer.

4. Conclusion

Several wake measurement example cases with varying inflow conditions have been presented in the current work along with a thorough description of the experimental setup. One of the primary objectives of the experiment is to collect validation-quality experimental data to improve the predictive capability of wind plant computational models to represent the response of the turbine wake to varying inflow conditions and turbine operating states. Considerable attention has been paid to the experimental setup and design in order to produce high quality data sets for this purpose. These data sets quantify the effect of a range of inflow conditions (including highly stable atmospheric boundary layers) and turbine operating states on the detailed, high-resolution development of the wake velocity deficit. These measurements are being used in a series of validation studies for both high fidelity wind plant models and lower fidelity controls models. The data sets produced during this test campaign are publicly available through the DOE Atmosphere to electron (A2e) Data Archive and Portal (DAP) at <https://a2e.energy.gov/projects/wake> [10].

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